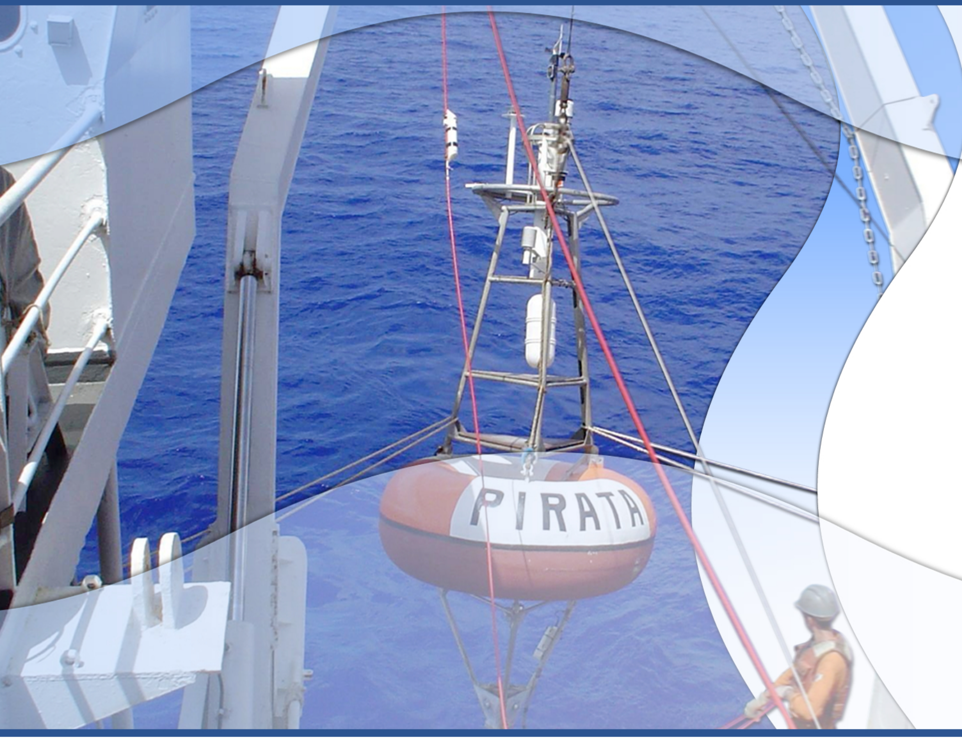

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THE OCEAN OBSERVING SYSTEM FOR CLIMATE

National Oceanic and Atmospheric Administration
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CHAPTER III:

Satellite Contributions to the Ocean Observing System for Climate, 2007 -2008

Satellite Contributions to the Ocean Observing System for Climate, 2007 -2008

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Introduction

Satellites, with their ability to observe the global ocean frequently and at a fine spatial resolution, continued in 2007-2008 to fill a critical role in the global ocean observing system for climate. Since the time of the last report, satellite observing systems have successfully met the continuity requirements for building climate data records (CDRs), but are facing many challenges. The successful launch of the Jason-2 satellite continues the ocean surface topography observational record, but the difficulties faced by the Sea-viewing Wide Field of View Sensor (SeaWiFS) instrument in the last year have given rise to new challenges for the ocean color community. While the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor on the NASA Aqua satellite has performed well in its place, significant concerns exist with regard to the next generation of ocean color sensors. Sea ice continues to be successfully monitored by satellites, and the last year has been an extremely productive one for the satellite sea surface temperature (SST) community, whose international pilot project has matured and is now delivering fully integrated, next-generation global and regional datasets.

Readers familiar with the last two annual reports will notice some changes in this year's report. The chapter will include the latest status, critical activities, and a look forward to the future for SST, ocean color, ocean surface topography, and sea ice but will leave an update on satellite marine wind observations to a future report. This year's report also omits the historical descriptions and rationale for each of the parameter classes. That information is relatively unchanging and interested readers should refer to previous reports if needed.

Sea Surface Temperature

Current Status and a Look Forward

SST remains perhaps the single most important parameter for ocean climate monitoring, with a continuous record of satellite monitoring dating back to 1981. Currently, the MODIS sensors on the NASA Terra and Aqua platforms continue to perform well and the Advanced Very High Resolution Radiometers (AVHRRs) on board Metop-A and NOAA-18 are in operational status. The Geostationary Operational Environmental Satellite (GOES) platforms, GOES-11 and GOES-12, continue to deliver SST measurements, as does the Advanced Along Track Scanning Radiometer (AATSR), the Tropical Rainfall Measuring Mission (TRMM) and its TRMM Microwave Imager (TMI), and the Advanced Microwave Scanning Radiometer-EOS (AMSR-E). Other platforms are also currently making SST observations.

Looking forward, the next generation National Polar-orbiting Operational Satellite System (NPOESS) program and its pre-cursor NPOESS Preparatory Project (NPP) will carry the Visible-Infrared Imager-Radiometer Suite (VIIRS), the successor to the AVHRRs and the MODIS sensors. The AMSR2 instrument on board the Japanese GCOM-W platform, expected to launch in 2012, will extend the time series of the current AMSR-E on the NASA Aqua platform. The European Space Agency's pair of Sentinel-3 satellites will each carry Sea and Land Surface Temperature Radiometer (SLSTR) instruments, designed to continue the AATSR time series after their launch in 2012. Finally, another AVHRR is available for the future launch of the final in the current series of NOAA polar orbiters, carrying the SST observations from AVHRR forward several more years.

Critical Activities

As in the past, consistently reprocessing individual sensor observations, combining multiple contemporaneous observations from different sensors, and merging time series from individual sensors into a consistent record remain high priority areas for SST climate record development. Since the time of the last report, there have been several important advances in these areas. International coordination of these activities has been achieved through the Global Ocean Data Assimilation Experiment (GODAE) High Resolution SST Pilot Project (GHRSST-PP; Donlon et al., 2007), which became active in 2002 and is now producing and distributing over 25 commonly formatted SST products, all with error uncertainties (http://www.ghrsst-pp.org). The GHRSST-PP has matured into a global operational "system of systems" and with the end of GODAE in 2008 has now become the Group for High Resolution SST (GHRSST). GHRSST includes both near real time operational products like the global ODYSSEA product (Figure 1, Autret and Piollé , 2008) as well as retrospective, reprocessed data sets like the NOAA National Climatic Data Center's Daily OI (http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php, Reynolds et al., 2007), which extends from present back to 1985 and relies on the reprocessed AVHRR Pathfinder time series.

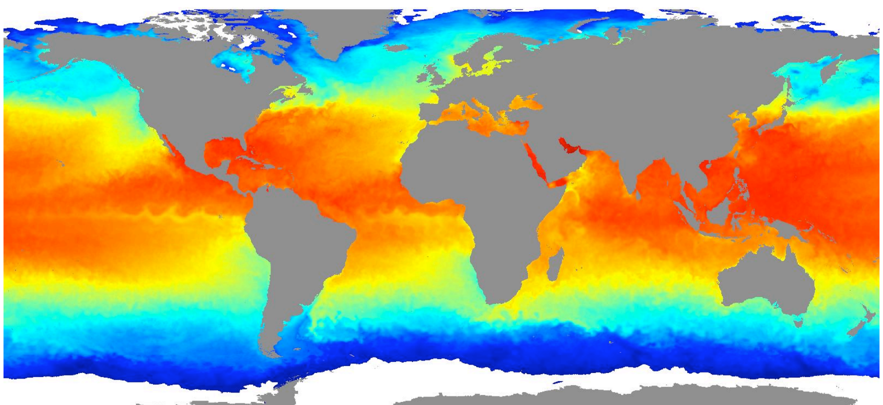

Figure 1: Global ODYSSEA Sea Surface Temperature Analysis for July 30, 2008, acquired from the GHRSST Global Data Assembly Center (http://ghrsst.jpl.nasa.gov). ODYSSEA is a daily global L4 product produced at IFREMER/CERSAT (France), and has a spatial resolution of 10 km.

NOAA's National Oceanographic Data Center (NODC) and the University of Miami continue to maintain the AVHRR Pathfinder effort, the single-sensor series reprocessing effort focused on creating global SST CDRs from the AVHRRs on the NOAA polar orbiters (http://pathfinder.nodc.noaa.gov). Currently, the Pathfinder project provides a global, approximately 4 km resolution time series spanning 1985-2007 on multiple averaging periods (daily, 5-day, 7-day, 8-day, monthly, and yearly) with corresponding climatologies. Pathfinder continues to be supported by NOAA and is being expanded to include 1981-1984. Recently NASA joined in support of the project to make the entire Pathfinder time series available in GHRSST formats with uncertainty estimates, an important requirement for a CDR. The need for reprocessing efforts like Pathfinder is clearly demonstrated in Figure 2, which illustrates the difference between day-night averaged satellite and in situ SSTs between 1985 and 2005, determined using Pathfinder AVHRR data (top panel) and operational AVHRR SST data (bottom panel). The same UK Met Office HadSST2 in situ reference dataset is used for both. The AVHRR Pathfinder differences from the in situ references are more consistent and lower overall (areas of gray) than the operationally produced AVHRR SSTs, which show large and variable biases (reds and blues). Groups around the world are now conducting similar reprocessing efforts for MODIS, TMI, AMSR-E, and the AATSR and its predecessors.

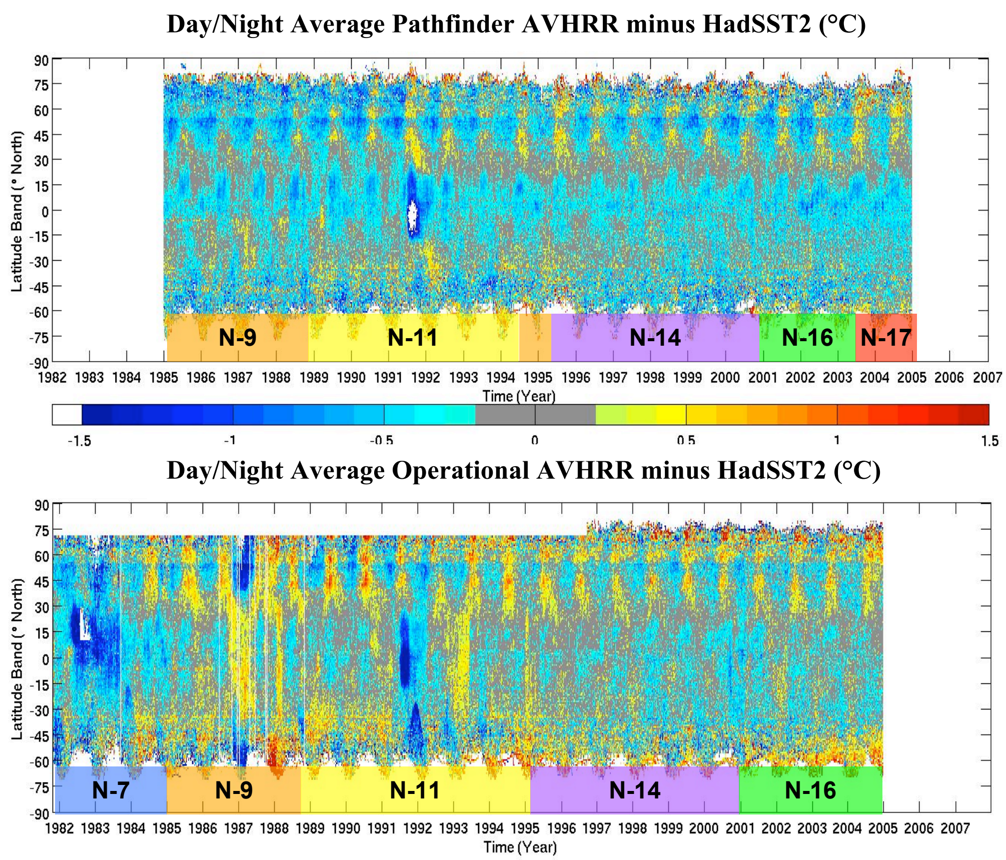

Figure 2: AVHRR Pathfinder (top) and Operational AVHRR (bottom) averaged into weekly, one-degree bins, are differenced with the in situ-based HadSST2 data (UK Met Office). These differences are then averaged into one-degree zonal bands and plotted against time, revealing overall lower differences and greater consistency in Pathfinder. The N-# markers indicate the NOAA-series satellite used in each data set for each time period.

The data sets produced by GHRSST and Pathfinder are examples of the many ongoing SST reprocessing and analysis efforts taking place around the world today. These efforts employ a wide range of methodologies and input platforms, and the many resulting data sets can lead to confusion and misinterpretation by users. The Global Climate Observing System (GCOS) SST and Sea Ice (SST-SI) Working Group recently released an intercomparison framework to address this problem. The GCOS SST-SI Working Group is recording and evaluating the differences among these various SST analyses, identifying the sources of those differences, and recommending actions to ensure the quality and consistency of the analyses. The data sets, along with several intercomparison diagnostics, are all made available in GHRSST format through NODC's GHRSST web pages (http://ghrsst.nodc.noaa.gov).

Ocean Color

Current Status and a Look Forward

Satellite-based ocean color observations have been demonstrated to be invaluable in climate studies by improving the understanding of ocean biology and biogeochemistry and the significant role of the ocean in the global carbon cycle. Ocean color data also provide the necessary information to evaluate impacts of climate change on coastal and ocean ecosystems, including influences of climate on eutrophication, harmful algal blooms, primary productivity, fisheries, and protected habitats. Accurately measuring ocean color properties remains, however, a demanding task. Key challenges include the need to correct for significant atmospheric effects, as well as to discriminate the various optical constituents, particularly in complex and dynamic coastal waters. Despite these challenges there has been a continuous climate-quality ocean color time series since 1997, but its continuity is currently at risk.

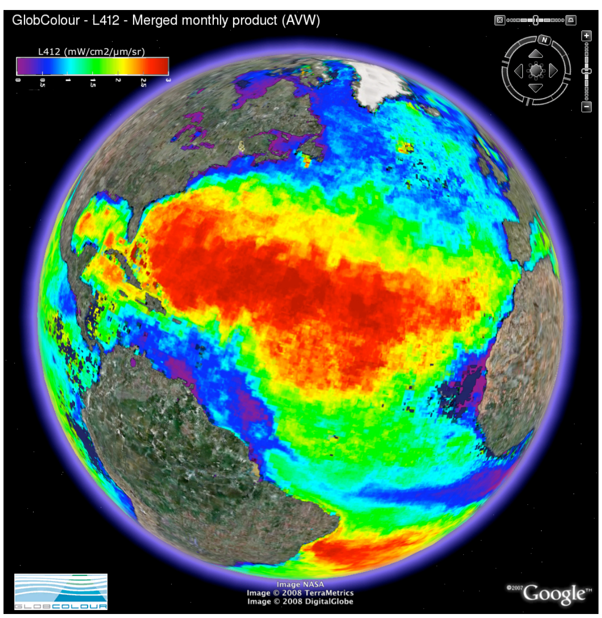

Figure 3: GlobCOLOUR normalized water-leaving radiance at 412 nm, from MERIS, MODIS, and SeaWiFS for July 2002

SeaWiFS has been operating in "safe haven", a non-imaging mode, for much of 2008 as a result of internal telemetry and navigation anomalies. The sensor itself, however, remains healthy and fully functional. There are plans to load a software patch in August 2008 to correct the recurring anomalies. Since SeaWiFS is commercially owned, availability of SeaWiFS data depends on purchasing licenses. As of this writing, it remains to be determined whether NASA (for access to delayed, reduced resolution global data) and/or NOAA (for access to near-real time full resolution data for U.S. coastal waters) will be able to extend their licenses beyond 2008. Fortunately, ocean color observations from MODIS-Aqua have been fully calibrated and now provide global data with quality comparable to SeaWiFS; the Aqua ocean color time-series runs from 2002 to the present. Efforts are also ongoing to address issues that have been identified with use of MODIS-Terra for ocean color applications (Franz et al., 2008).

For continuity of U.S. ocean color observations, the VIIRS instrument will fly on the next generation NPOESS environmental satellites, starting with the launch of the NPP spacecraft. However, VIIRS-NPP does not appear capable of providing climate-quality ocean color data for the research and applications communities, due to manufacturing anomalies and other concerns voiced by members of the ocean color community (see NRC, 2008, for further details). Launch of the operational VIIRS sensor on the NPOESS C1 platform in the afternoon orbit is anticipated no earlier than 2013. Due to program restructuring, a planned NPOESS mid-morning orbit with a VIIRS instrument was eliminated, leading to a significant reduction in desired temporal and spatial coverage for ocean color observations (NRC, 2008).

In Europe, the Medium Resolution Imaging Spectrometer (MERIS) on Envisat-1 has been operating since 2002 and is currently providing high quality data for a variety of applications. A follow-on to MERIS is currently being developed: the Ocean and Land Colour Instrument (OLCI) on the Sentinel-3 platforms. In addition to the exciting development of these operational ocean color sensors, efforts are underway to develop the next generation of space-based ocean biology and biogeochemistry missions (e.g., hyperspectral instruments), as existing capabilities do not entirely meet the needs of the research and application user communities (see IOCCG, 2008; NRC, 2008). Next-generation missions, both R&D and operational, will likely provide improved spatial, temporal and spectral resolution and coverage. For a comprehensive list of other current and planned sensors providing ocean color data of various resolutions and quality, see the International Ocean Colour Coordinating Group (IOCCG) website (http://www.ioccg.org). Cross-calibration is critical for climate applications, and these other sensors have not all been fully calibrated to meet the standard of SeaWiFS data quality.

Critical Activities

Efforts are underway by space agencies and other partners to address potential gaps in the ocean color time-series, as well as to develop the next generation of research missions and transfer existing ocean color observing capabilities from the research domain into operations and applications. In this context, the IOCCG is helping to coordinate development of an Ocean Colour Radiometry (OCR) Virtual Constellation by the Committee on Earth Observation Satellites (CEOS), as a contribution to the Global Earth Observing System of Systems (GEOSS). The purpose and value of the OCR Virtual Constellation is to ensure a long-term record of calibrated ocean color radiances to determine the impact of climate change on ocean ecosystems and biogeochemical cycles.

Other development and application efforts are underway across the globe, with the IOCCG sponsoring many working groups focused on items like global ecological provinces, geostationary ocean color observations, calibration of ocean color sensors, placement of bio-optical sensors on Argo floats, regional ocean color algorithms, atmospheric corrections, phytoplankton functional types, and the merging of ocean color data from multiple sensors in support of global carbon-cycle and climate change research. Some recent examples of merging efforts include work by NASA's Ocean Biology Processing Group (OBPG), the NASA REASoN research awards to develop merged SeaWiFS and MODIS products, and the work of the European-sponsored GlobCOLOUR project whereby merged global SeaWiFS, MODIS, and MERIS products (e.g., Figure 3) are now available from 1997 to 2007 (http://www.globcolour.info). GlobCOLOUR time-series production will continue as part of the European Global Monitoring for Environment and Security (GMES) Marine Core Service initiative from 2009 onwards, including daily delivery in near-real time to support operational oceanography, and may include development of higher-resolution coastal products. The international scientific community is also pursuing a variety of satellite-based ocean color climate research efforts. Studies are underway using ocean color data to assess whether there is a shift in the distribution patterns and phenology of phytoplankton biomass. One example is focused on the cosmopolitan coccolithophorid species *Emiliania huxleyi*, which is potentially susceptible to ocean acidification.

These diverse activities and capabilities are crucial to develop and sustain important ocean-color derived biological and biogeochemical parameters to support climate research and applications, particularly generating community consensus CDRs and the GCOS Essential Climate Variables.

Ocean Surface Topography

Current Status and a Look Forward

On time scales greater than a decade, the near global coverage provided by satellite altimeters makes it possible to estimate global sea level rise. Monitoring the ocean surface topography from space also provides invaluable observations of inter-annual to decadal time scale phenomena such El Nino/Southern Oscillation and the North Atlantic Oscillation. To maintain continuity of these critical observations, the Jason-2 Ocean Surface Topography Mission (OSTM), the follow-on to Jason-1, was successfully launched on June 20, 2008. Jason-2/OSTM is the result of a four-partner collaboration: NASA and CNES are primarily responsible for building and launching the satellite, while NOAA and EUMETSAT are primarily responsible for collecting and processing the near real-time data. At the time of this writing, Jason-2/OSTM is flying in tandem with Jason-1, in the same orbit approximately 55 seconds apart, making nearly simultaneous measurements to precisely inter-calibrate the two satellites. After 6 months of tandem operation, Jason-1 will be moved to an interleaved orbit, effectively doubling the spatial resolution of the satellite pair. All preliminary results indicate that Jason-2/OSTM is performing at least as well as Jason-1, and that it will be successful in carrying out its primary mission of maintaining the high accuracy, global sea level time series established by TOPEX and Jason-1, hopefully for at least 5 years. NOAA and EUMETSAT are currently in the early stages of planning for a jointly funded Jason-3 mission to be launched in 2013 to overlap with Jason-2/OSTM.

In addition to Jason-2/OSTM and Jason-1, there are currently two other altimeter satellites operating, but at less than full functionality: Envisat, the successor to ERS-1 & ERS-2, now only operating on one radar altimeter frequency; and Geosat Follow-On, the successor to Geosat. Ocean surface topography data from these sensors is now widely available.

Because current altimeters provide height measurements only at the nadir location along their ground track (and not a ‘swath’ of data, as is typical of other satellite instruments) there is always a trade-off between spatial and temporal resolution. Fortunately, for the large-scale processes generally of interest for climate observations, a single high-accuracy altimetry mission such Jason-

2/OSTM is sufficient. Shorter space and time-scale phenomena at the ocean's mesoscale are not adequately sampled by a single altimeter, but the present configuration of three altimeters in complementary orbits does capture most of the signals of interest. Applications such as ocean eddy monitoring, surface current analyses, and ocean heat content for hurricane intensity forecasting require this higher resolution sampling (see http://ibis.grdl.noaa.gov/SAT for more information on altimetry research and applications). In the next few years, however, it is likely that Geosat Follow-On, Envisat, and Jason-1 will fail, leaving possibly only one altimeter, Jason-2/OSTM, operating in the near term. The requirement for high spatial resolution coverage may be satisfied by NASA's proposal to fly a swath altimeter (SWOT), but not before late in the next decade.

Critical Activities

By paying careful attention to instrumental and environmental (e.g. path delay) corrections normally applied to an altimeter's range measurement, it is possible to construct a consistent record of global mean sea level change over the past 16 years from the TOPEX and Jason-1 altimeter missions. As shown in Figure 4, the overall trend for this interval is 3.2 mm/year, roughly 1.8 times greater than the 20th century rate and 3 times greater than the late 1800's – early 1900's rate, both determined from tide gauge observations (Scharroo et al., 2006). Whether the present higher global rate reflects a true long-term change or simply decadal variability is presently unknown.

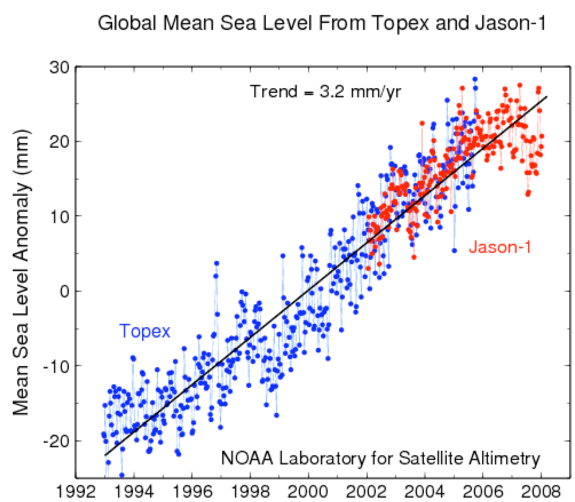

Figure 4: Global mean sea level trend from TOPEX and Jason-1.

The problem is complicated by the non-uniform spatial pattern of sea level trends (not shown). The question of what is causing these patterns is currently a topic of active research involving the combined use of altimetry to determine the total sea level change, Argo profiler measurements to determine the steric- (i.e. density-) related contribution, and GRACE gravity measurements to determine the mass contribution. For example, the upper panel in Figure 5 shows the total sea level trends (those due to both density and mass change) computed for the last four years of Jason-1 measurements, 2004 to 2008, during which time the Argo profiler array was fully deployed. The lower panel shows the steric sea level trends from Argo measurements over the same 4 year interval. Though the spatial patterns are similar, the *global mean* total sea level trend over the period is +2.5 mm/year, while the *global mean* steric component is +0.7 mm/year. This suggests that roughly three quarters (1.8 mm/yr) of the current global trend in sea level is due to mass increase, presumably from continental ice melt. For comparison, the 20th century sea level budget was roughly two-thirds (1.4 mm/yr) mass increase and one-third (0.4 mm/yr) steric increase (Miller and Douglas, 2004).

To ensure accuracy and value of altimeter observations for climate studies, particularly for the global sea level rise problem, it is important to have a period of overlap between satellite missions.

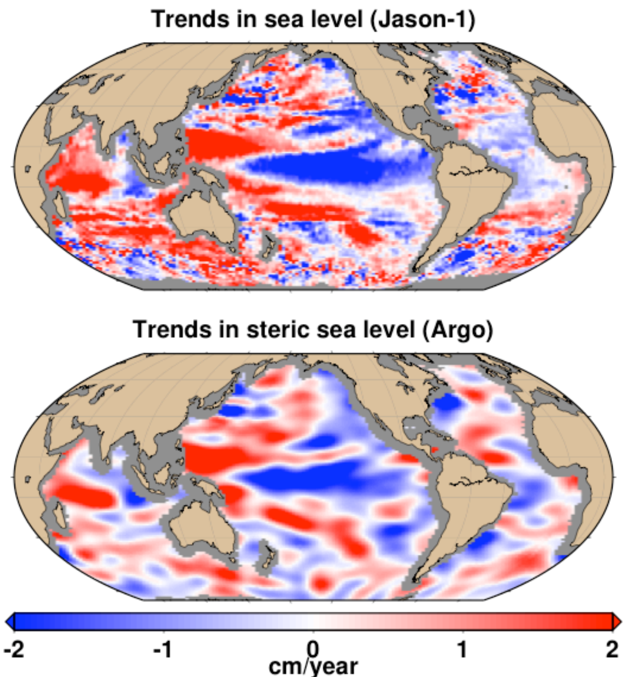

Figure 5: Spatial distribution of trends from January 2004 through December 2007 in total sea level from Jason- (upper panel) and steric sea level from Argo (lower panel).

Only by directly comparing the average heights between missions is it possible to accurately detect and correct for biases and thereby extend the global sea level record over multiple decades. An overlap is also useful for identifying subtle instrument-dependent problems, such as a drift in one of the environmental corrections to the range measurements. A problem of this type was detected in the Jason-1 microwave radiometer measurements, during the 4-year overlap between the Jason-1 and TOPEX/Poseidon missions. A method of compensating for this drift has now been put into place.

The value of satellite altimeter observations for climate studies is also greatly enhanced by the operation of two in-situ ocean observing systems supported by the NOAA Office of Climate Observations (OCO): a global network of GPS-controlled tide gauge stations, and the Argo profiling drifter array. Relative sea level observations from more than 80 tide gauge stations are currently providing an independent, ground-based check on the bias and drift errors of each altimeter mission. Routine comparisons between gauge and altimeter measurements show that altimeter-measured trends are accurate within +/-0.4 mm/year. Thus, the 3.2-mm/year trends observed over the past 15 years by satellite altimetry (Figure 4) is significantly higher than the gauge-measured trend over the past century. The gauge measurements may also provide a critically needed solution to the problem of how to deal with gaps in the global mean time series caused by instrument failure or the delay of a follow-on mission. Figure 6 shows some preliminary results from a study now underway, using tide gauge records to connect the Geosat and TOPEX records. Gauge-altimeter differences are used to correct a large drift error in the Geosat data and separately determine the bias difference between the two altimeters. Although much work remains to be done, the technique looks promising.

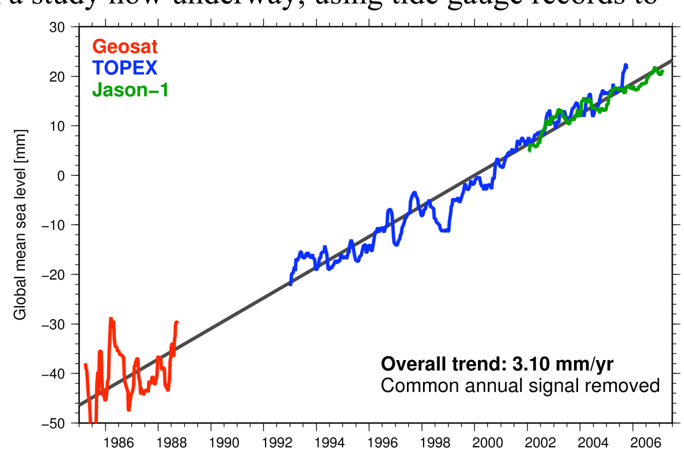

Figure 6: Global mean sea level change from Geosat, TOPEX, and Jason-1 altimeters, based on a simultaneous fit to a single trend and annual function and separate bias estimates for each satellite. The Geosat record was previously corrected for a 7.48 mm/yr drift error determined from tide gauge-altimeter differences (Miller et al., 2007)

Sea Ice

Current Status and a Look Forward

Monitoring sea ice is a critical climate indicator, and recent events in the Arctic highlight the need for long-term, continuous observations. The series of passive microwave imagers that began with the Scanning Multichannel Microwave Radiometer (SMMR) in 1978 continues to the present with the latest Special Sensor Microwave/Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) platforms. These passive sensors allow for the determination of sea ice extent, but not thickness. Both extent and thickness are needed to determine sea ice volume, which is of fundamental importance to climate models. The NASA Ice, Cloud and land Elevation Satellite (ICESat), launched in 2003, continues to collect ice and snow elevation measurements over polar regions using the Geoscience Laser Altimeter System (GLAS). The European Space Agency plans to launch the CryoSat-2 satellite in March of 2009, which will carry the SAR/Interferometric Radar Altimeter (SIRAL) for measuring ice shelf and sea ice mass. The CryoSat-2 mission is devoted to the monitoring of sea ice thicknesses and polar ice sheet elevations.

The National Snow and Ice Data Center (NSIDC) continues to update the Sea Ice Index, which uses the combined SMMR-SSM/I record and NASA Team (NT) algorithm to show trends and anomalies (Figures 7 and 8) on a monthly basis. The Sea Ice Index site (http://nsidc.org/data/seaice_index/) had over 106,000 distinct users (summed monthly) in 2007, and reached a high of more than 45,000 unique users for the month of June 2008 alone, reflecting a growing public awareness of changes in the polar regions. The data product can be viewed using Google Earth as well. NSIDC also produces and maintains monthly Arctic sea ice climatologies based on the National Ice Center (NIC) sea ice charts, which are produced through the analysis of several satellite passive and active data sources. The NIC Arctic climatologies for the period 1972- 2007 are available at http://nsidc.org/cgi-bin/bist/bist.pl?config=nic_climo.

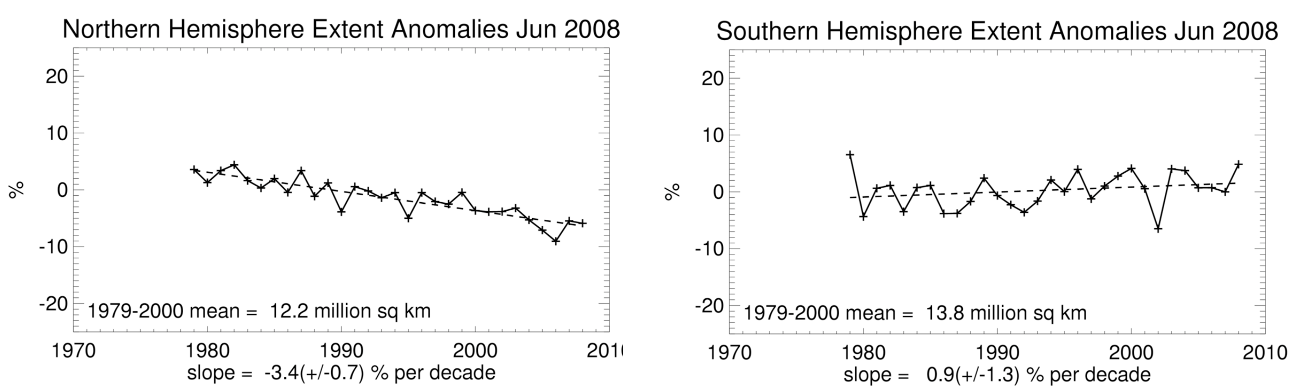

Figure 7: Northern Hemisphere (left) and Southern Hemisphere (right) sea ice extent trends from the Sea Ice Index (nsidc.org/data/seaice_index/), based on satellite passive microwave sea ice retrievals.

Critical Activities

The dynamic nature of sea ice and the logistical difficulties of conducting in situ measurements on the ice make validation of satellite sea ice freeboard measurements challenging. To address this challenge, the joint NOAA/NASA Arctic Aircraft Altimeter (AAA) Campaign was carried out in March of 2006 using an instrumented NASA P-3 aircraft to underfly Envisat and ICESat satellites. Recent validation studies at NOAA resulting from this campaign have yielded excellent agreement between freeboard heights derived from Envisat radar altimeter (RA2) observations and corresponding estimates made with NASA's Airborne Topographic Mapper (ATM), a well calibrated airborne laser altimeter (e.g. Figure 8). Similarly, excellent agreement has been found in comparisons of airborne laser altimeter measurements with ice and snow elevation estimates from the ICESat GLAS instrument (e.g. Figure 9).

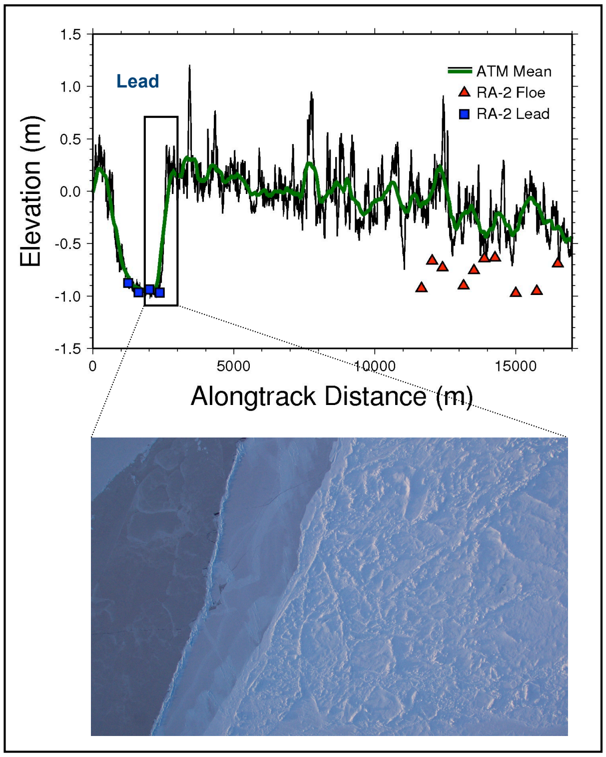

Figure 8. Top panel shows ATM elevation profile along a 17 km Envisat ground track. Blue squares denote Envisat lead locations and red triangles denote ENVISAT sea ice floes. Lower panel illustrates a digital photograph of the lead-floe transition of the upper panel (black box).

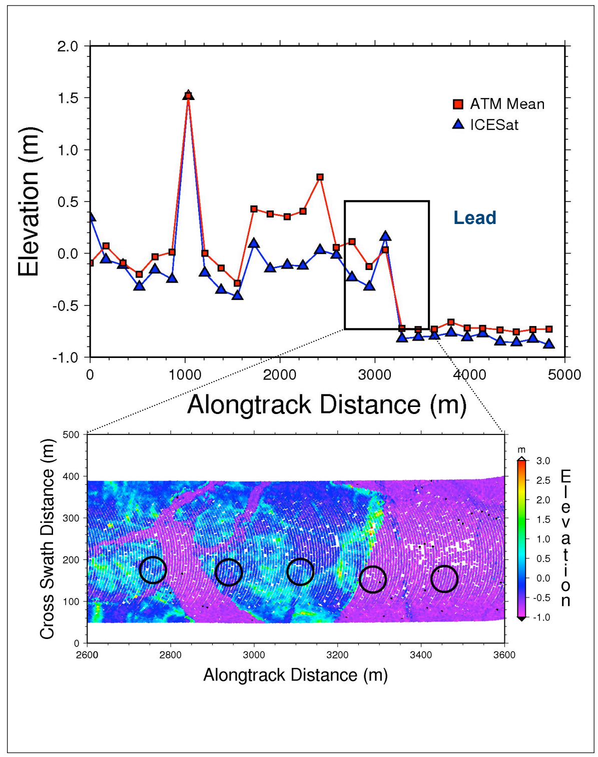

Figure 9. Top panel shows mean ATM elevations (red) and individual ICESat footprint elevations (blue) along a 5 km ICESat ground track. Lower panel illustrates the ATM swath measurements in the sea ice floe – lead transition region bounded by black box in upper panel. The ICESat footprints are denoted as black circles.

A joint NOAA-NASA airborne and in situ experiment is scheduled for April of 2009 and will include satellite altimeter under-flights over sea ice during the 2009 Applied Physics Laboratory Ice Station (APLIS) in the Beaufort Sea and in the Canada Basin and Lincoln Sea. This APLIS/Canada Basin Sea Ice Thickness (CBSIT) Experiment is designed to more thoroughly and precisely validate RA2 and GLAS ice freeboard observations. The experiment, which includes plans for in-situ and under the ice validation observations, will be an important step towards more fully exploiting data from the CryoSat-2 mission that will be launched the same year.

Activities of the GCOS SST-SI Working Group are critical to improving concentration estimates from passive microwave data for model assimilation, especially at the ice edge. An algorithm called NT2 uses the higher frequency channels available on SSM/I and later sensors to overcome weather and snow effects, and is being used with AMSR-E data. NSIDC has received funding from the NOAA Scientific Data Stewardship Program to intercalibrate SSMR-SSM/I with AMSR-E, develop data quality fields, and improve metadata and preservation standards. These steps are required to have sea ice extent and concentration meet NRC requirements for CDRs.

It is critical to extend the SSM/I-derived record into the operational life of the NPOESS program's MIS instrument. Future MIS sea ice products should be prototyped using AMSR-E. This work should be done by sea ice and remote sensing experts in sea ice algorithm development. The current NPOESS launch, scheduled for years after the Aqua design life ends in 2008, will likely leave a gap between AMSR-E and MIS coverage. DMSP should cover this gap, but the operational nature of the DMSP program has meant that overlaps between sensors have been short. The inter-calibration of SMMR and SSM/I ice records is based on only a six-week overlap period in 1987. Short overlap times impinge on CDR quality; an overlap of at least 1.5 years provides substantially better capability to account for sensor differences.

Synthetic aperture radar (SAR) data and imagery is another valuable tool for monitoring sea ice in near-real time, as well as assessing its seasonal and interannual variability in the context of climate variability and change. While there are currently numerous satellite sensors (e.g., ASAR on Envisat, PALSAR on ALOS) providing such data to users, and likewise plans for continuity internationally (e.g., Sentinel-1, Radarsat constellation), routine and sustained access to data for U.S. research and applied users is an ongoing concern as the U.S. does not currently have its own SAR sensor/mission.

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